# Next Generation Technologies to Predict and Locate Cable Failures

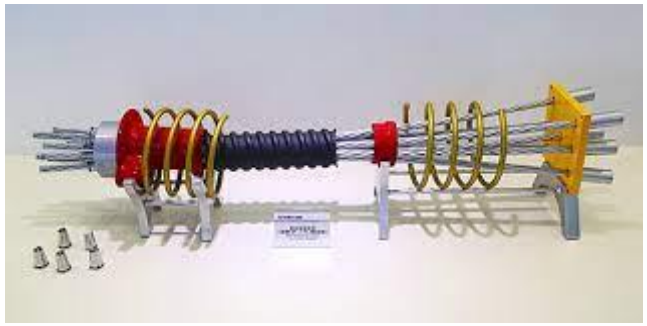
Dr. Cynthia Furse --University of Utah

EMLab.eng.utah.edu

# Cables, Wires, Connections

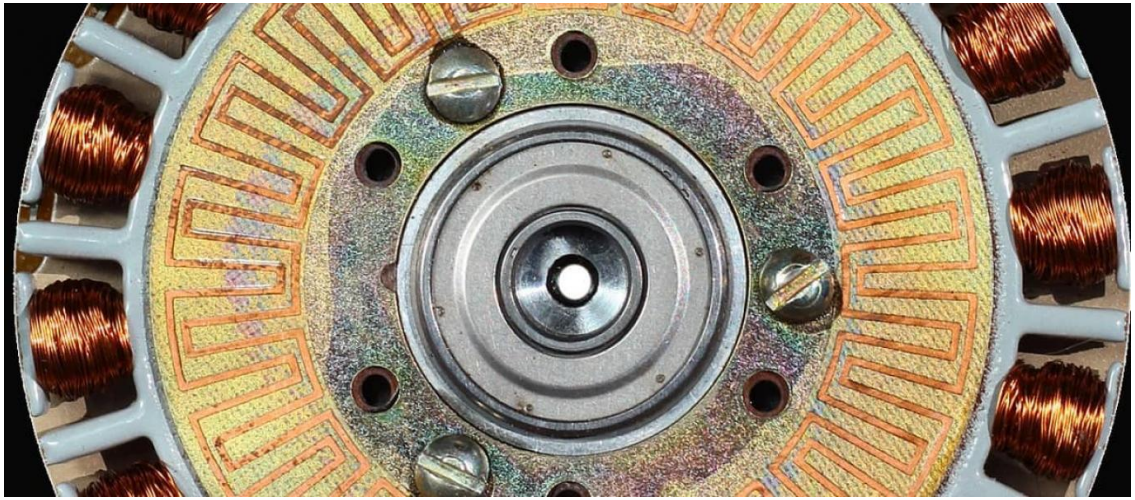
Power Grid

Vehicles



Structural Health Monitoring

Electrical Machinery

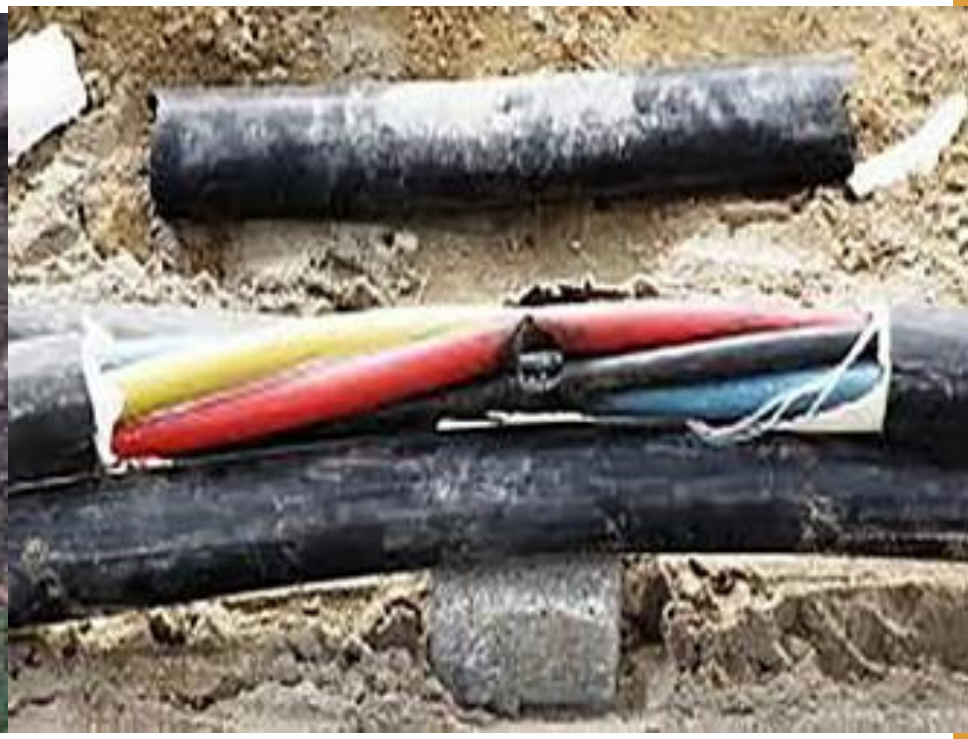


Credit: GE Research

# Cables, Wires, Connections

## Underground Cables

Credit: Wikiwand.com



Credit: ScanPlus Tech

# Sometimes Things Go Awry…

Fires

Breakdowns

Damage or Failure

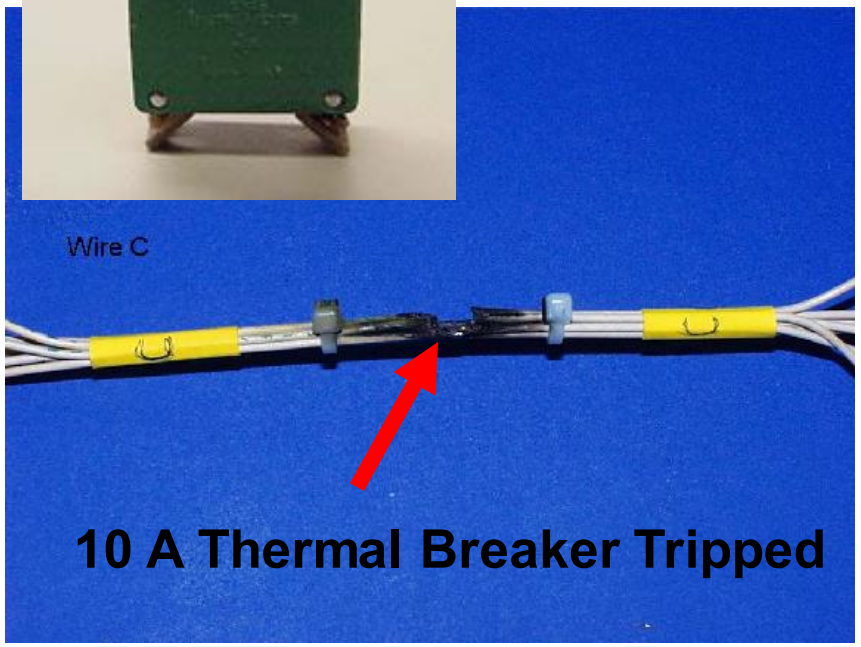
Downtime

# Electrical Protection

Circuit Breakers, Fuses, Arc Fault Circuit Breakers, Reclosers, Rapid Shutdown, Overcurrent Protection,….

# Detection, Protection, Location

## Arc fault Protection Prevents Fire
## …
## But How to Locate This??




10 A Thermal Breaker Tripped


AFIC Tripped on “Wet Arc”

*We Need a Method to LOCATE Faults on Live Wires*
*Many of these Faults will be Intermittent…*

# Electrical Test

Credit: TestGuy

- *Voltage, Current, Power Testing*
- *Visual Inspection*
- *Resistance/Impedance Testing*
- *Reflectometry (electrical or optical)*
- *And Other non-electrical test methods (acoustic, etc.)*

# Electrical Test

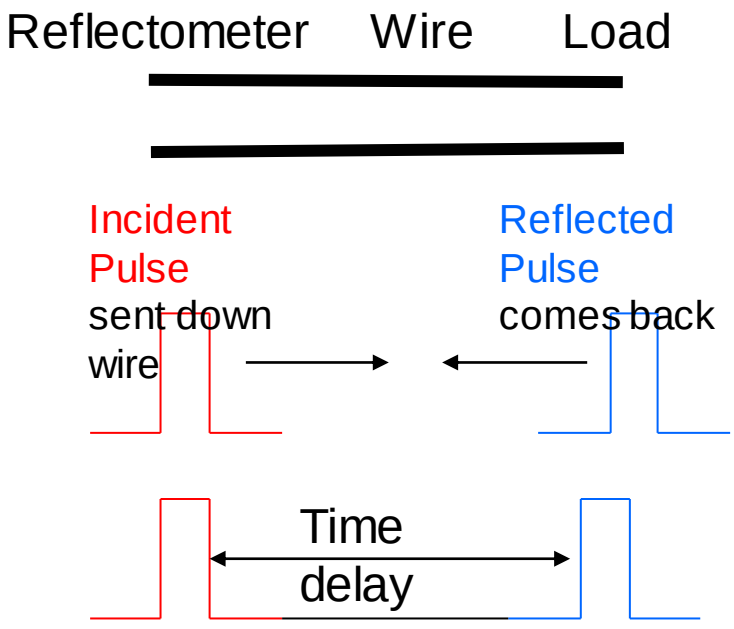
- *Voltage, Current, Power Testing*
  - *Good for Detection, Limited for Location*
- *Visual Inspection*
  - *Not very useful for underground cables*
- *Resistance/Impedance Testing*
  - *Good for detection, Limited for Location*
- *Reflectometry*
  - *Can be used for detection & location*

Credit: TestGuy

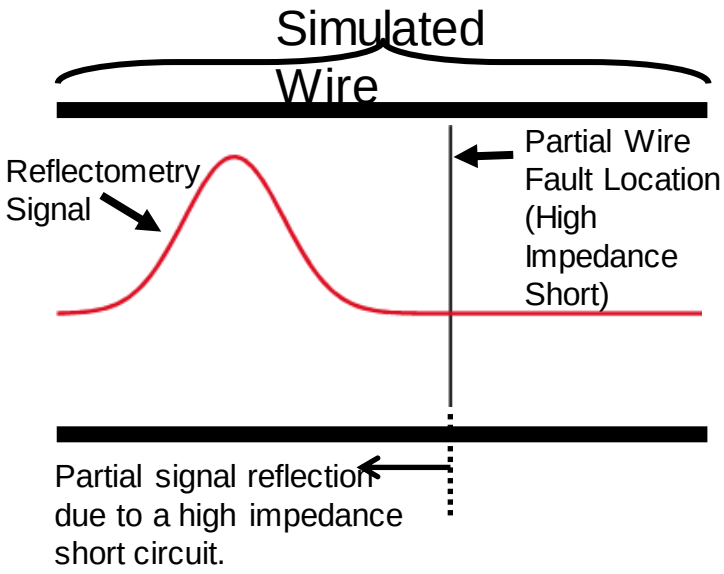
# Reflectometry

- *Similar to radar, but for electrical wires*

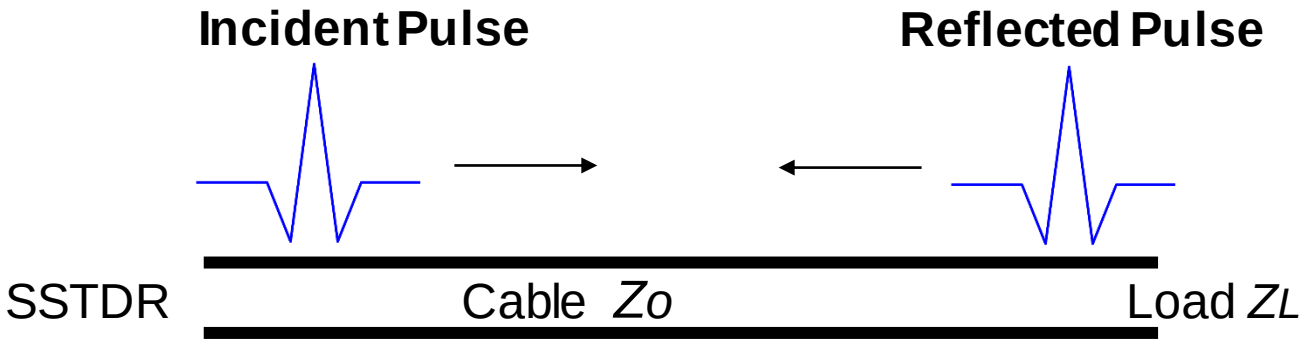
# Reflectometry




Time delay between Incident and Reflected Pulses tells distance to fault.

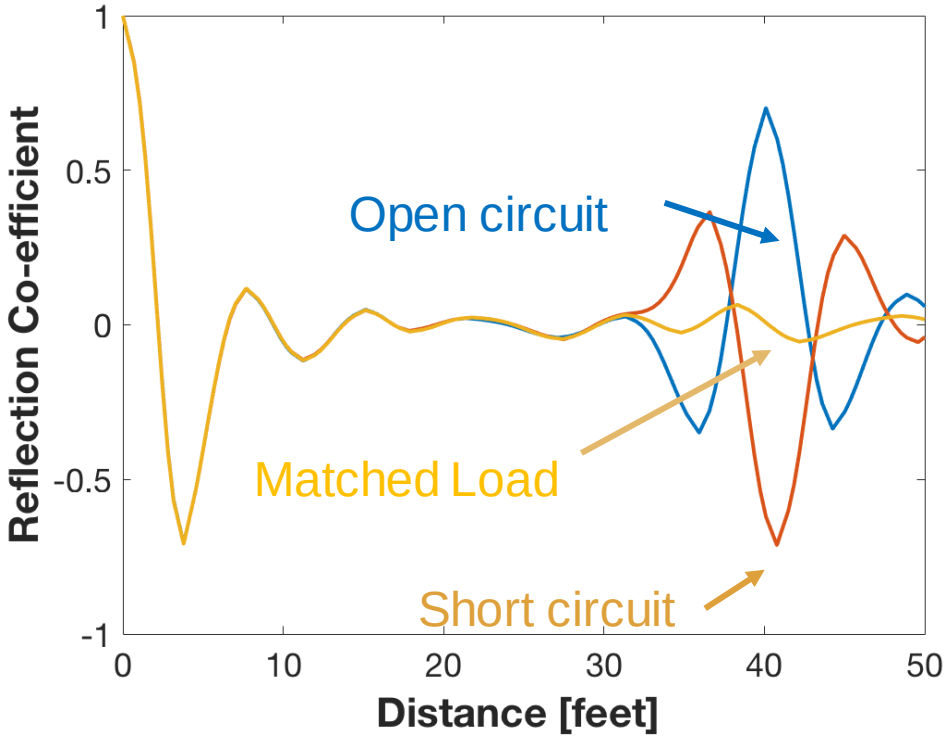


# Reflectometry

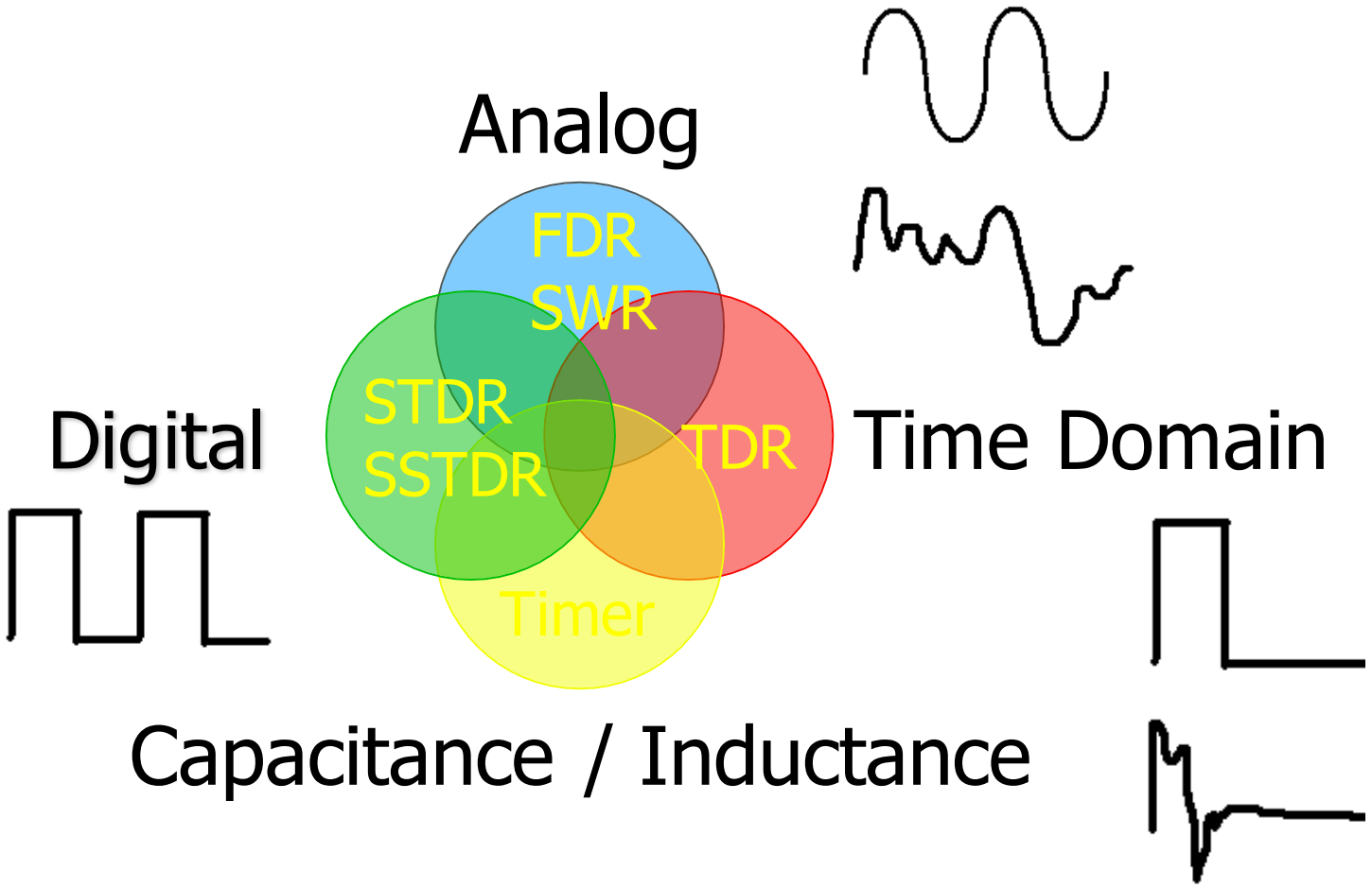



$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

Reflection Coefficient tells the fault type & magnitude

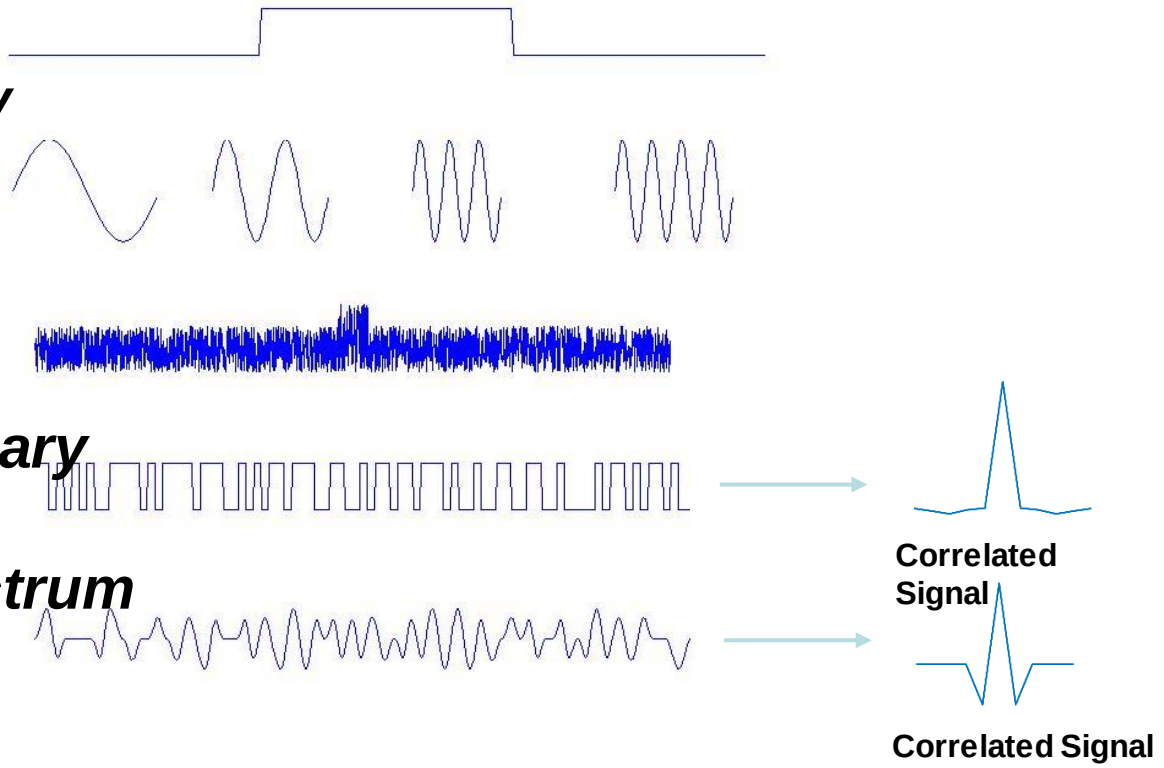


# Reflectometry Approaches



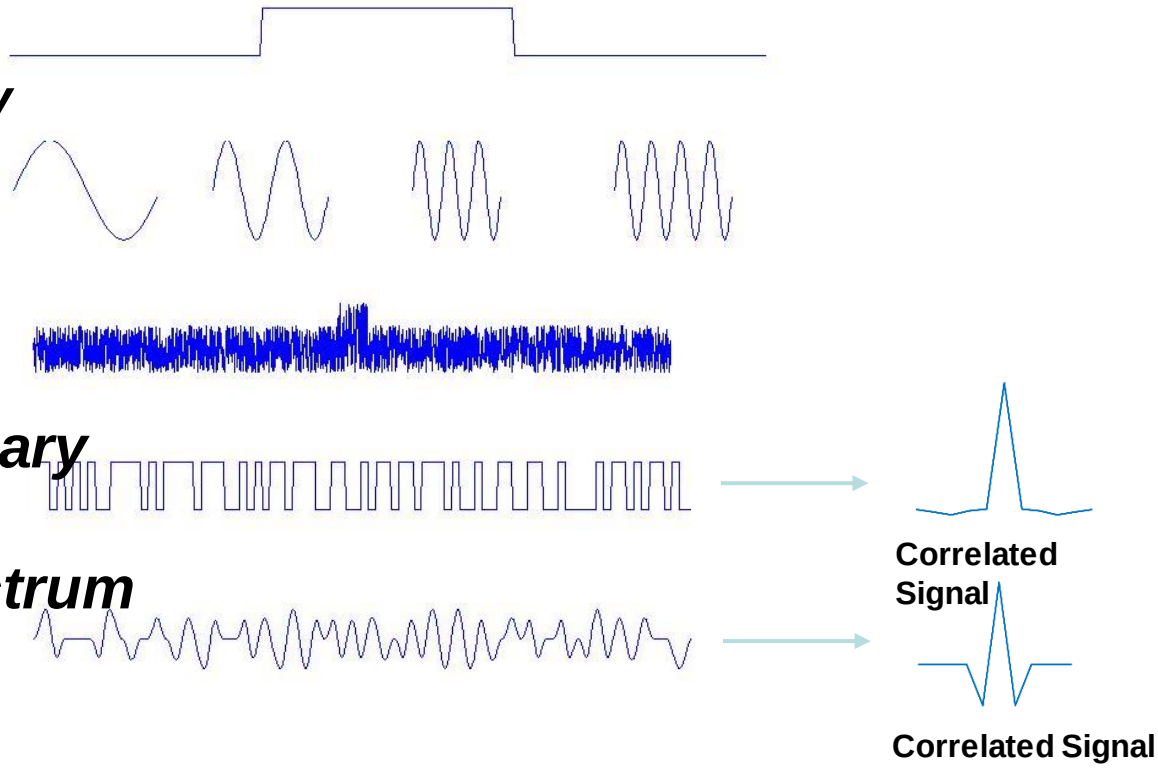
# Types of Reflectometry

- ***TDR: Time***
  - ***Time-Frequency***
- ***FDR: Frequency***
- ***NDR: Noise/Chaos***
- ***STDR: Sequence/Binary***
- ***SSTDR: Spread Spectrum***



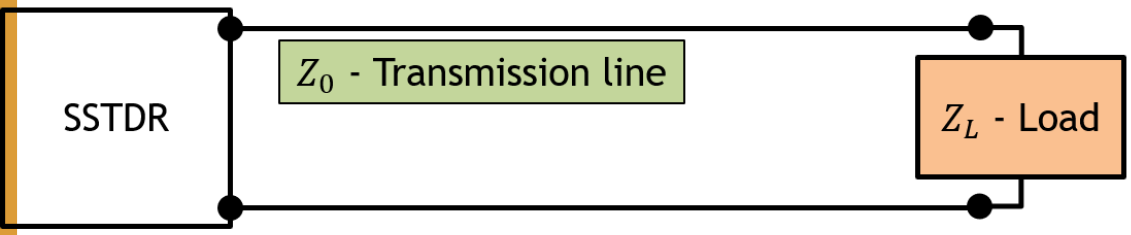
# Reflectometry: What Matters?

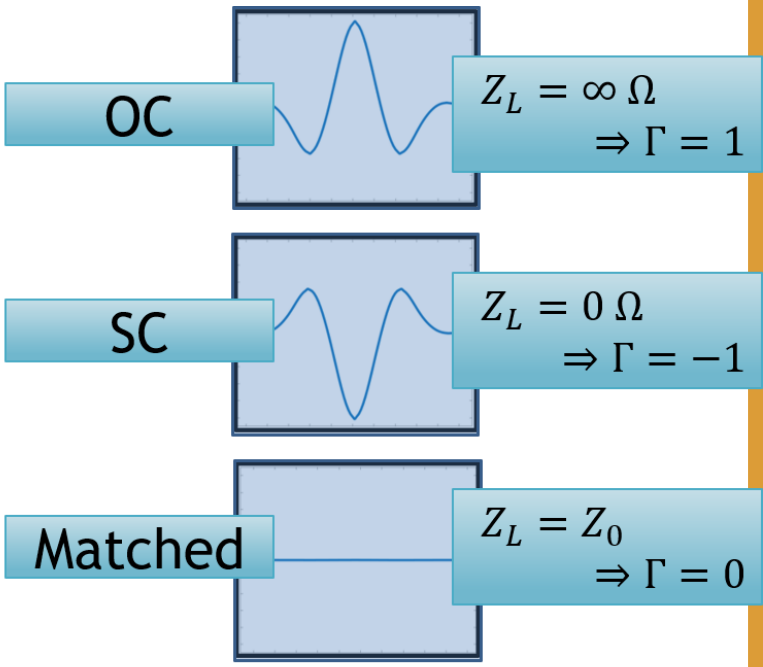
- ***TDR: Time***
  - ***Time-Frequency***
- ***FDR: Frequency***
- ***NDR: Noise/Chaos***
- ***STDR: Sequence/Binary***
- ***SSTDR: Spread Spectrum***




Bandwidth
Sampling
Dynamic Range (Signal to Noise Ratio)

# Time and Frequency Conversions




- Reflection Coefficient – $\Gamma$
  - Ratio of impedance between the transmission line $(Z_0)$ and the load $(Z_L)$

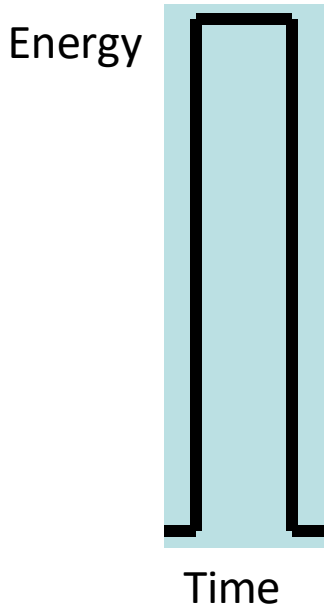
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

**Analysis in Time, Frequency or Both**

Evan Benoit, et al, "Inversion Theory and SSTDR Analysis," *IEEE APS*, 2020

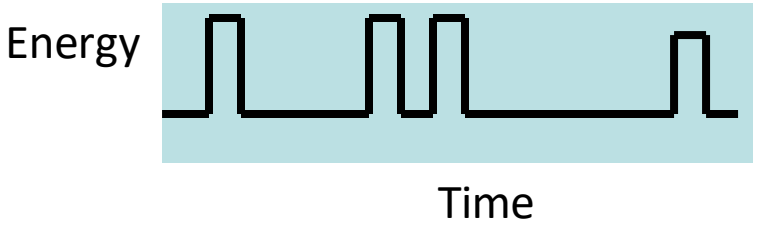
# Energy in the Signal

## TDR



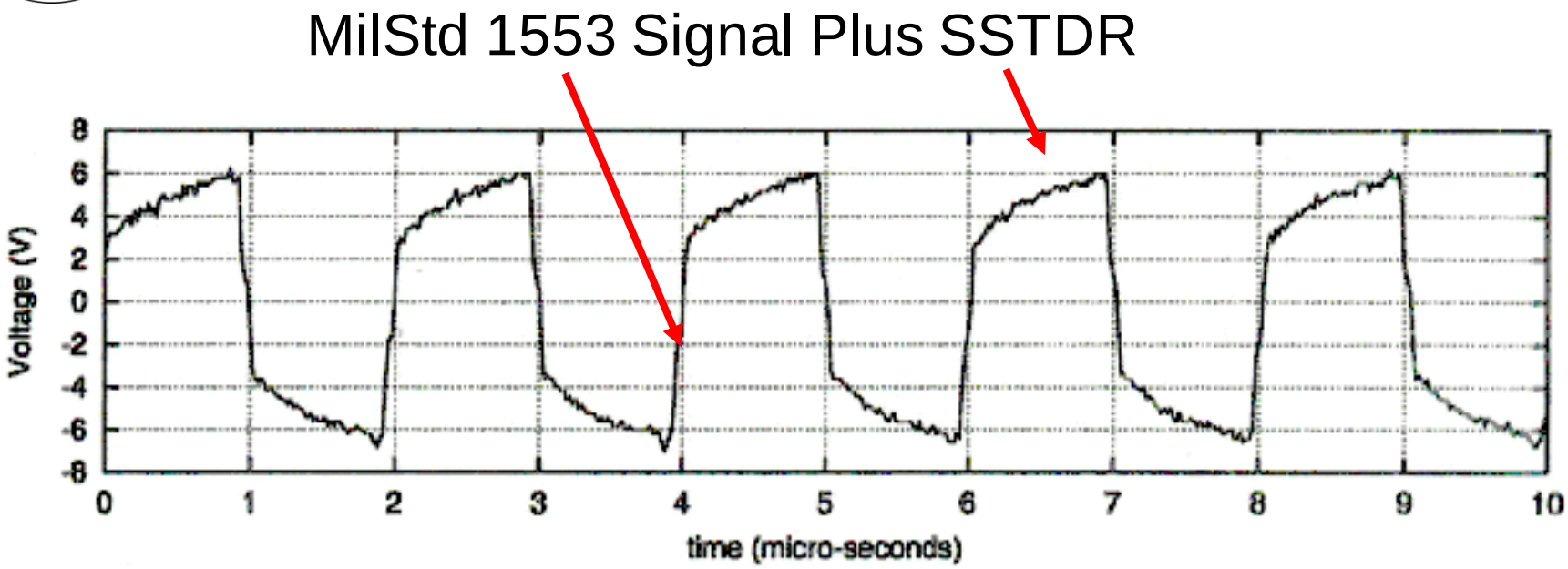

**Narrow Time:**
Interferes with other signals
Interfered with by other signals

## S/SSTDR




**Broad Time:**
Minimal (“no”) interference with other signals.

# Low Interference with Other Signals

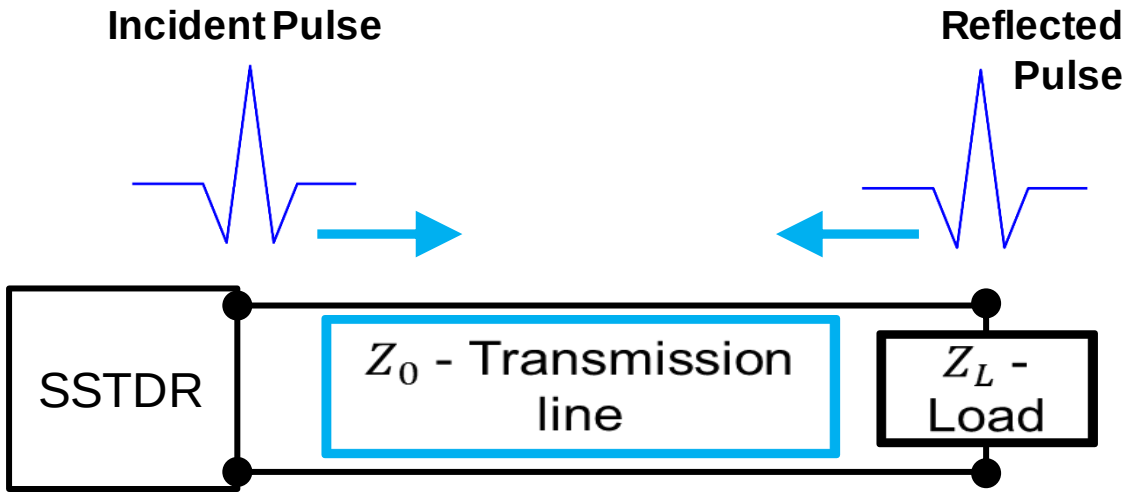



SSTDR can be used on LIVE systems

Paul Smith, et al, "Analysis of Spread Spectrum Time Domain Reflectometry," *IEEE Sensors Journal,* 5(6), Dec. 2005

# What is SSTDR

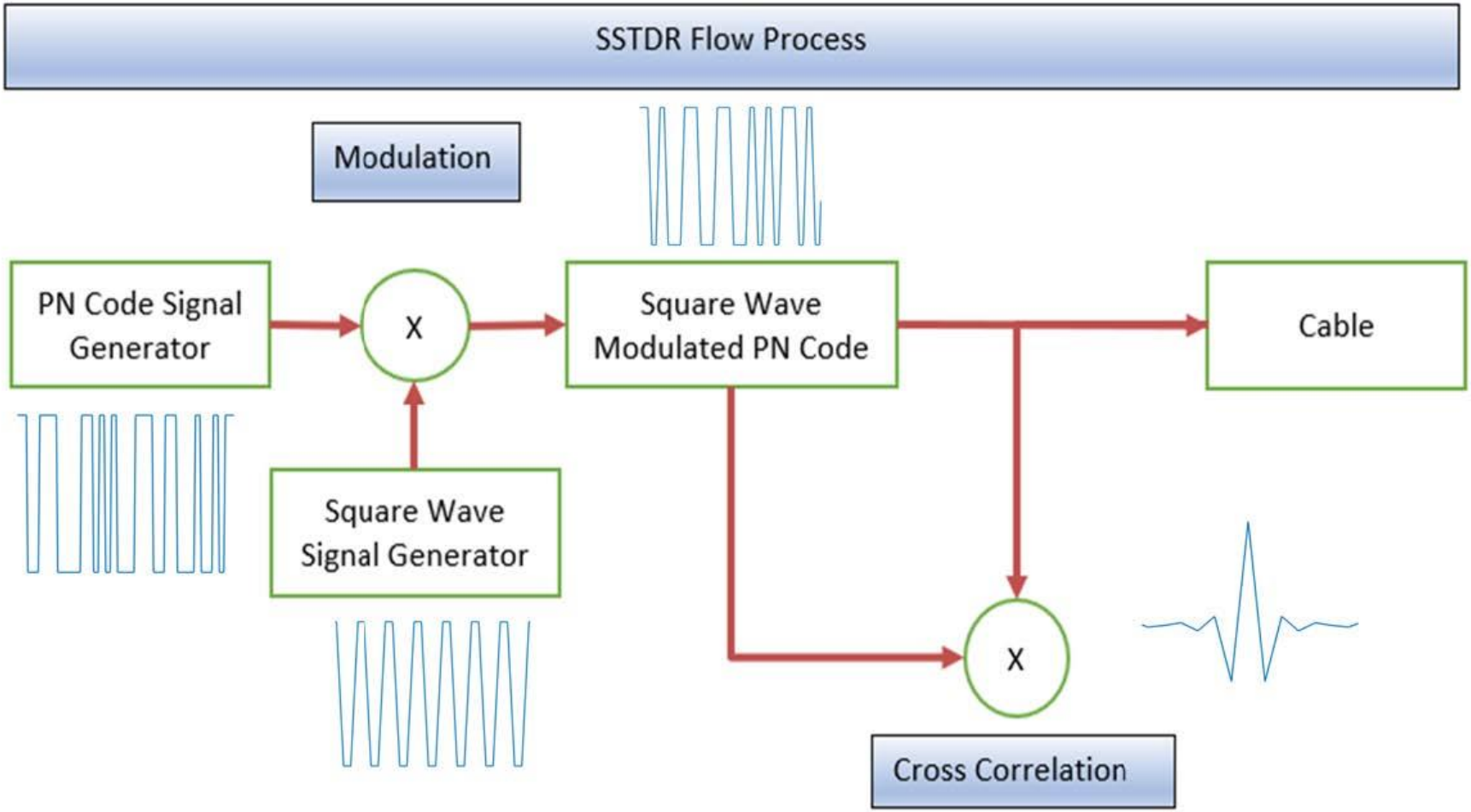
Spread Spectrum Time Domain Reflectometry




- *Similar to radar, but for electrical wires*

Disclosure: I co-founded LiveWire Innovation, based on this research, and therefore have a financial conflict of interest.

# How does SSTDR work




A. S. Edun, et al., "Finding Faults in PV Systems: Supervised and Unsupervised Dictionary Learning with SSTDR"

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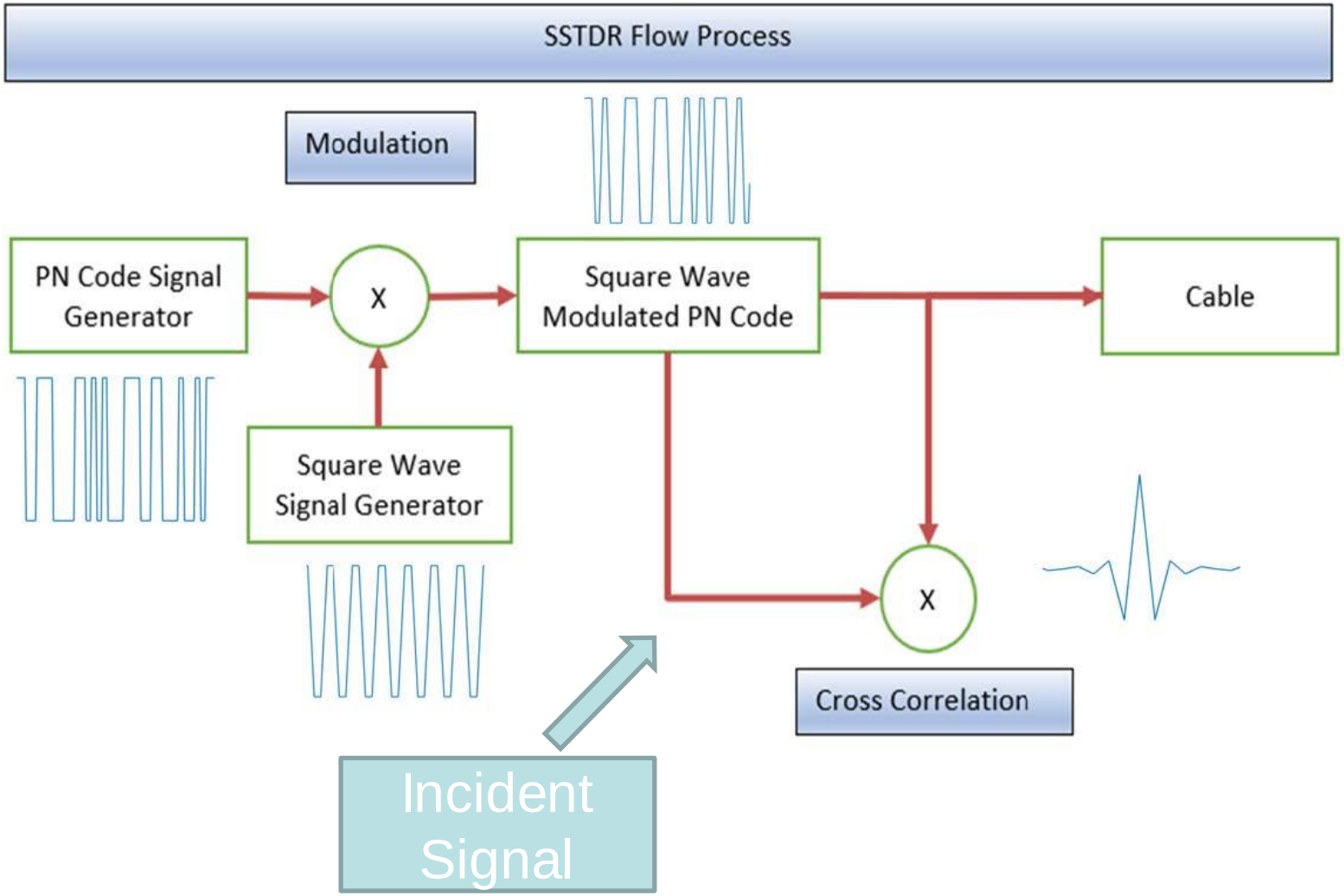


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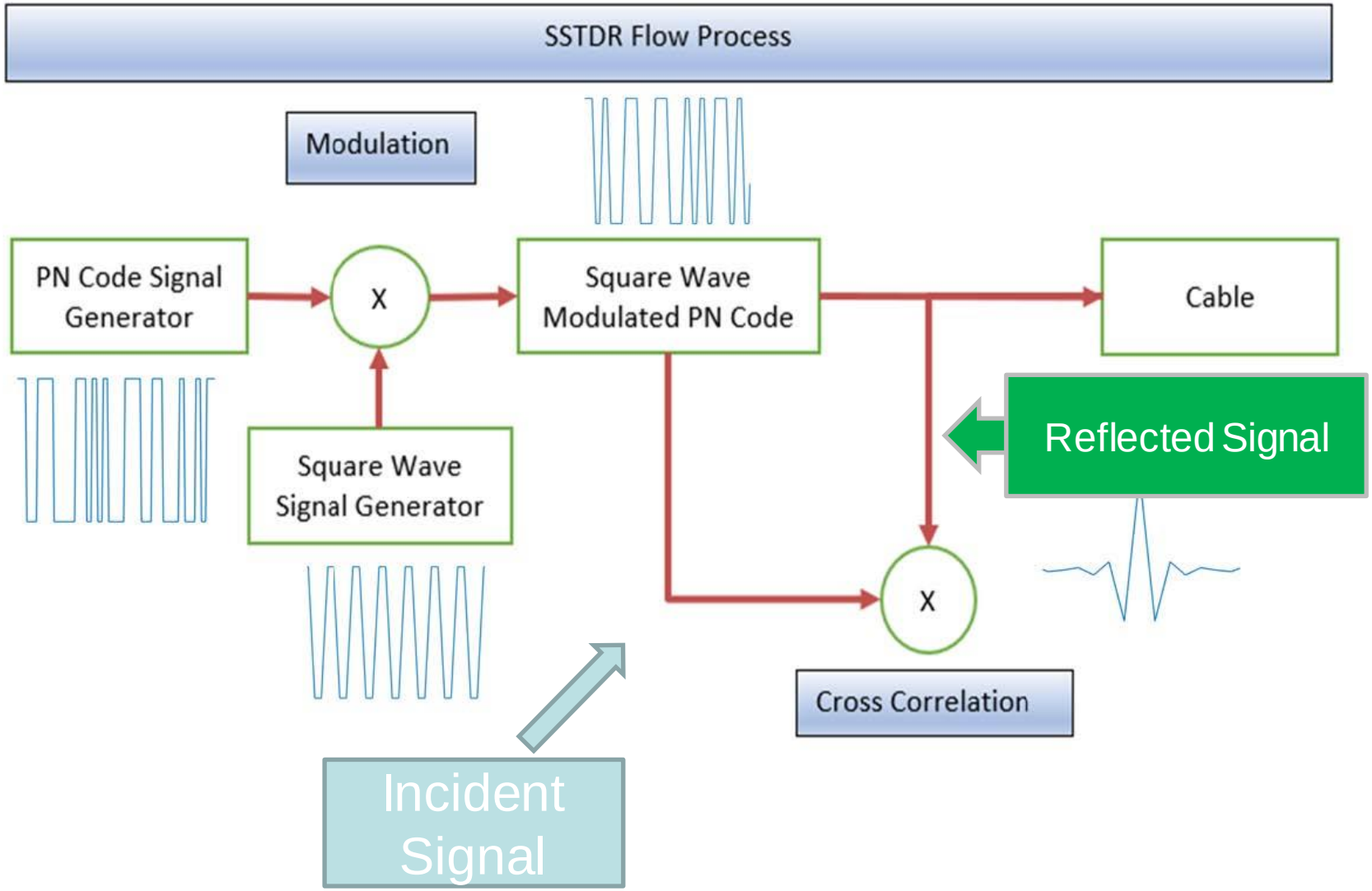
# How does SSTDR work




A. S. Edun, et al., "Finding Faults in PV Systems: Supervised and Unsupervised Dictionary Learning with SSTDR"

# SSTDR Cross Correlation

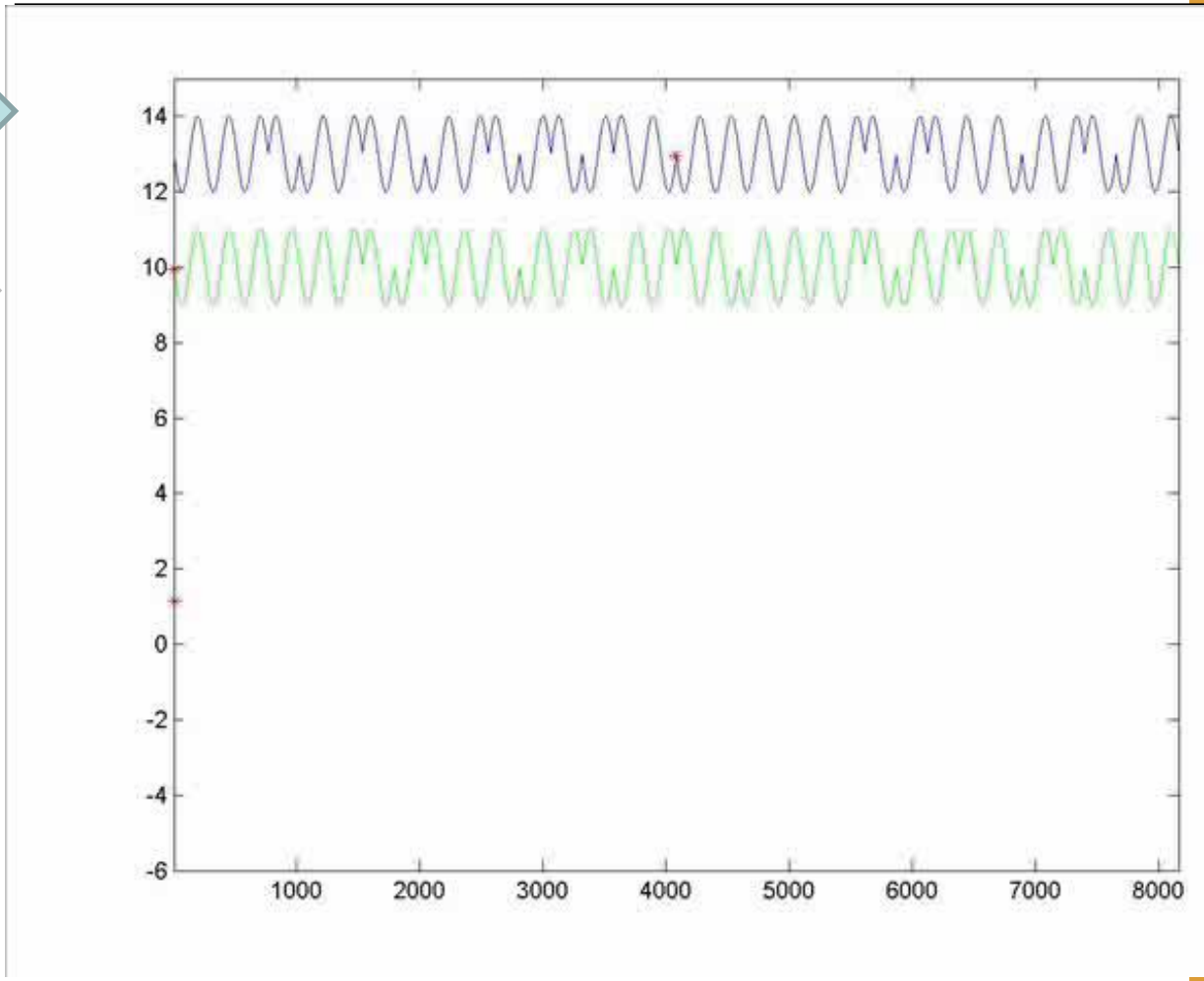
Incident Signal

Reflected Signal

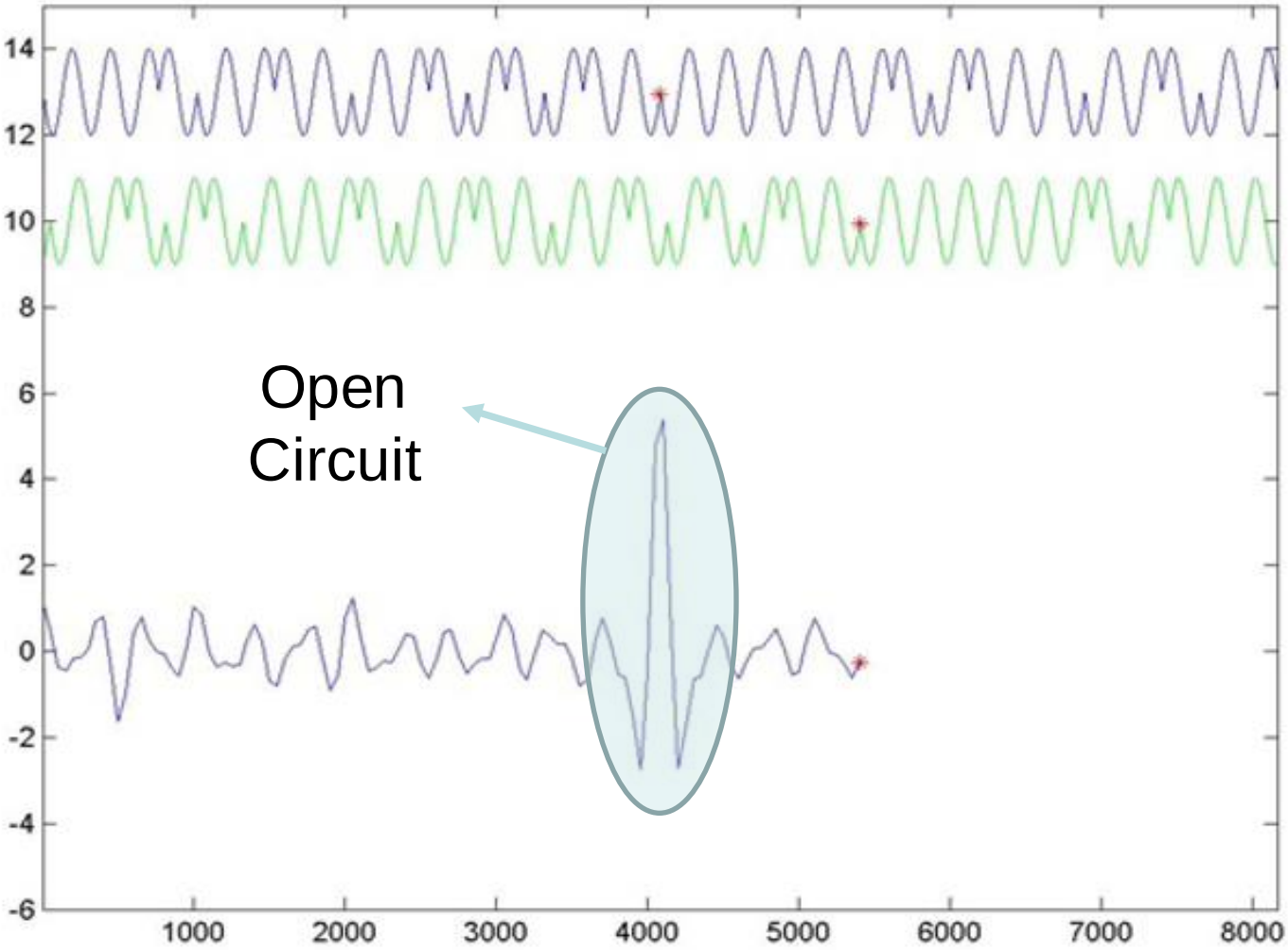
Incident Signal

Correlated Signal

Reflected Signal



# SSTDR Analysis



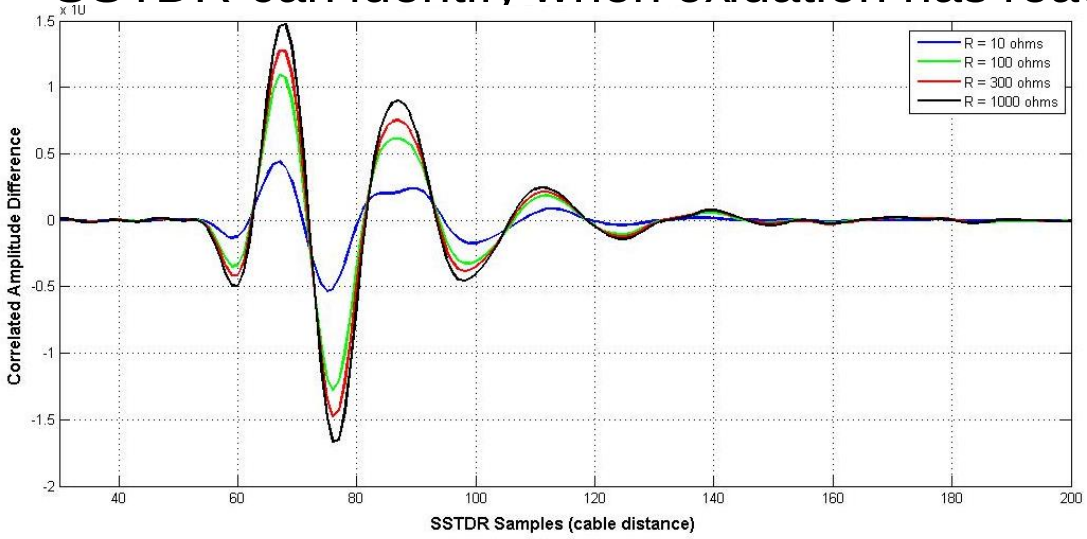
# What Kind of Faults?

## Open and Short Circuits

# Detect Oxidized or Corroded Electrical Connectors

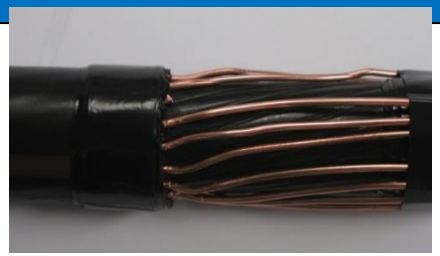
- As connector pins oxidize the electrical resistance increases

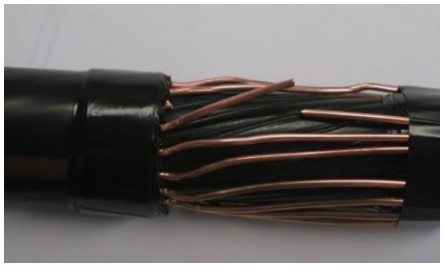
- SSTDR can identify when oxidation has reached a critical level

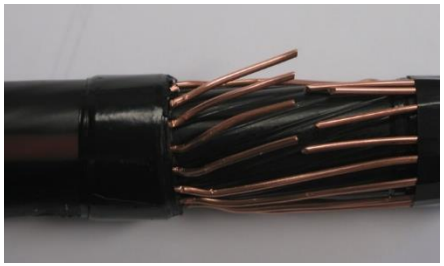



LIVEWIRE INNOVATION™

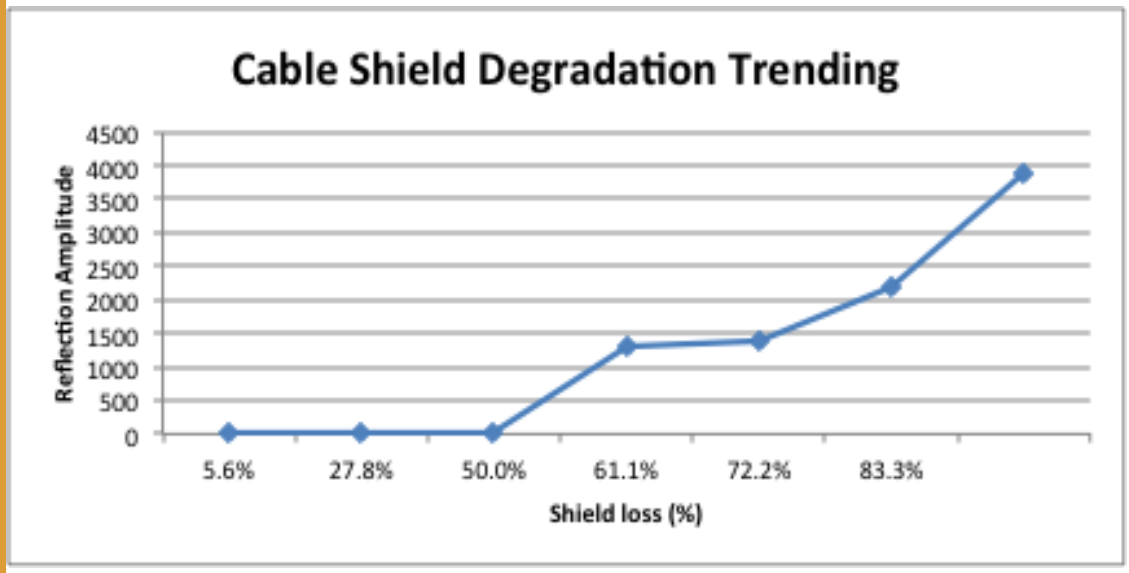
# Gradual Degraded Neutral (Shield) Testing at General Cable







- *Cable Type: EPR 15kV*
- *18 Total Copper Shield (Neutral) Wires*
- *SSTDR Reflection Amplitude Increases as the Copper Neutral Wires are Cut*

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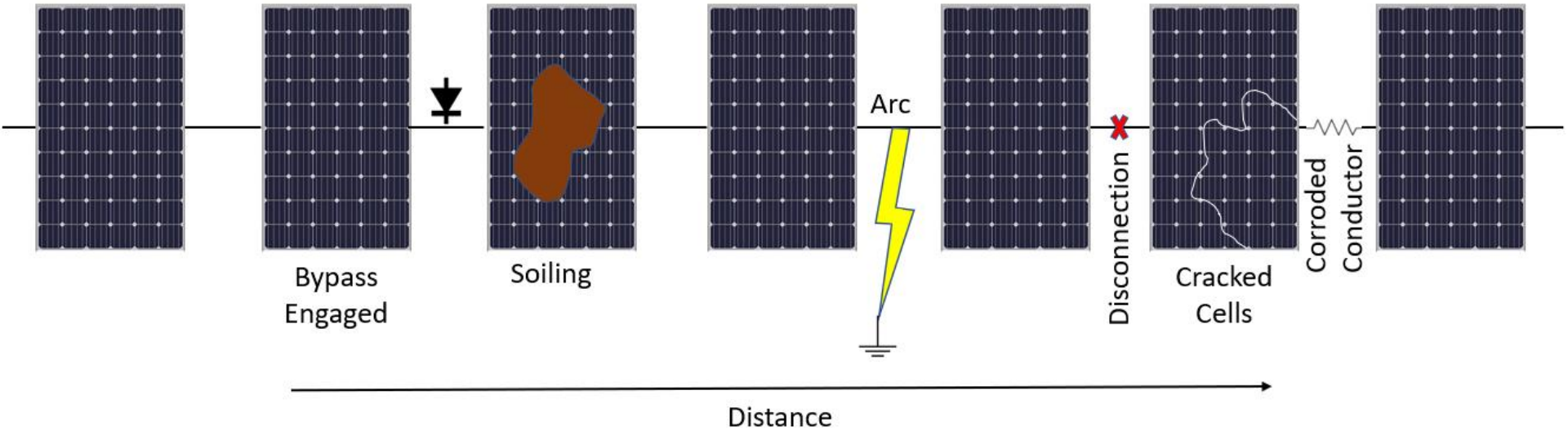
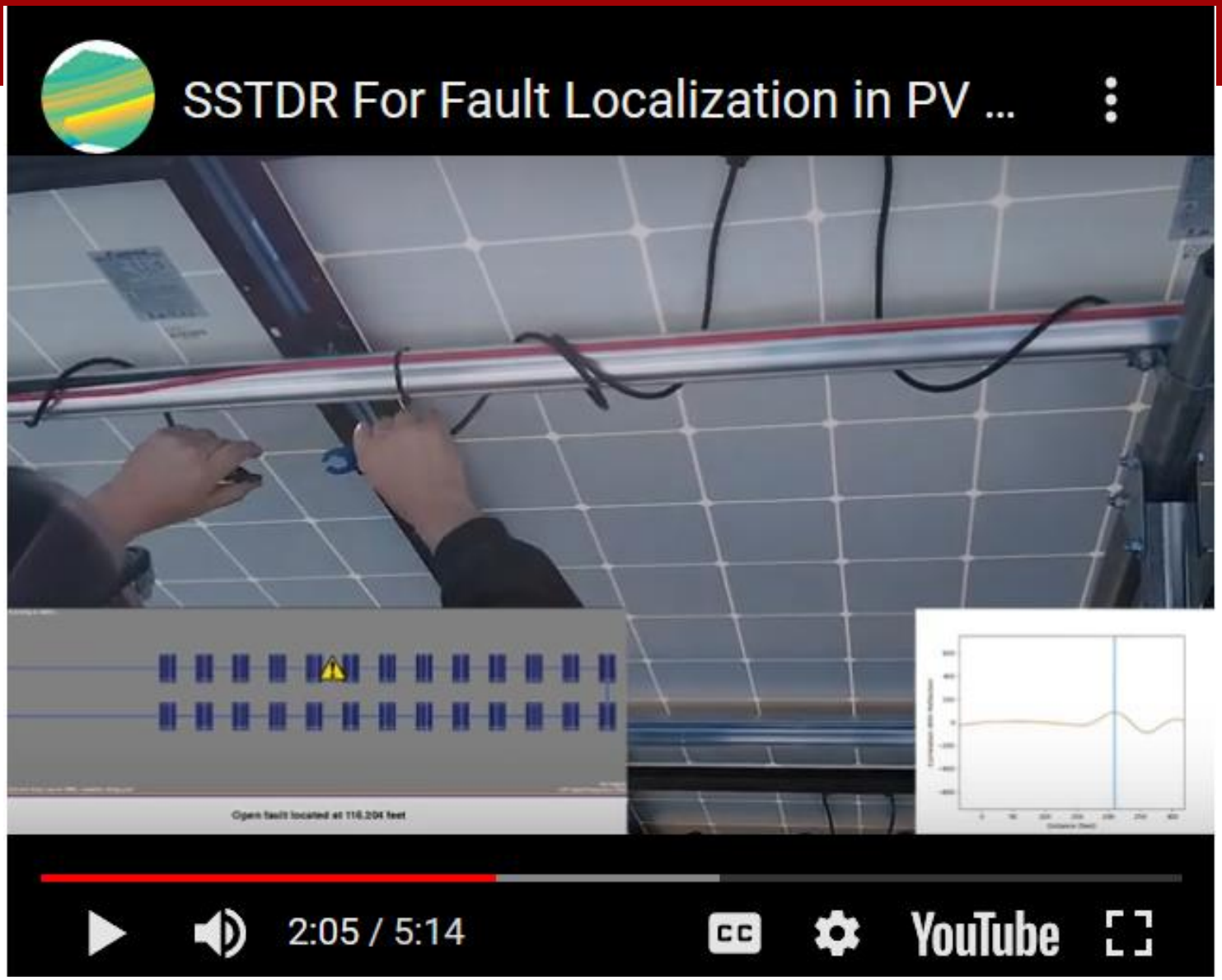
# PV Arrays


Mashad Uddin Saleh, et al, “An Overview of SSTDR Responses to Photovoltaic Faults" *IEEE JPV,* 2020

# Faults in PV Arrays



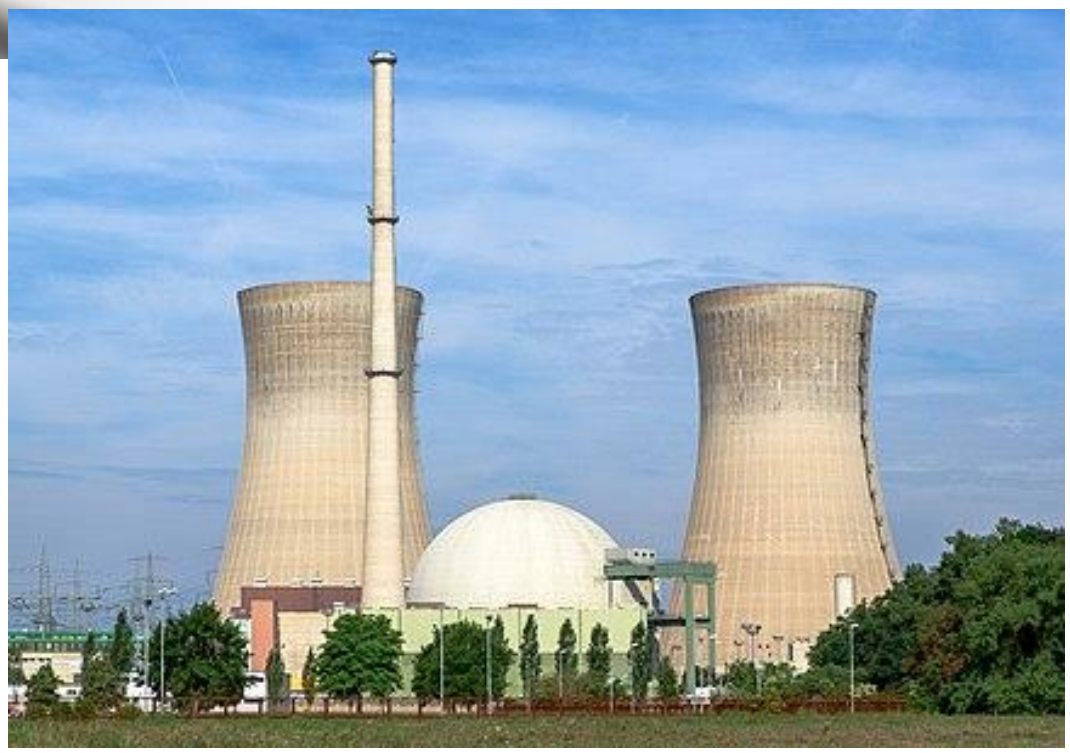

- Disconnections, soiling, arc fault, ground fault, corroded conductors/ connectors, cracked cells, degradations etc.




Video Credit: Cody LaFlamme (EMLab.eng.utah.edu)

# Cable Degradation in Nuclear Plants

EPRI, Fauske-Westinghouse, LiveWire, PNNL



# Rail Cable Theft

Viper Subsea
www.networkrail.co.uk

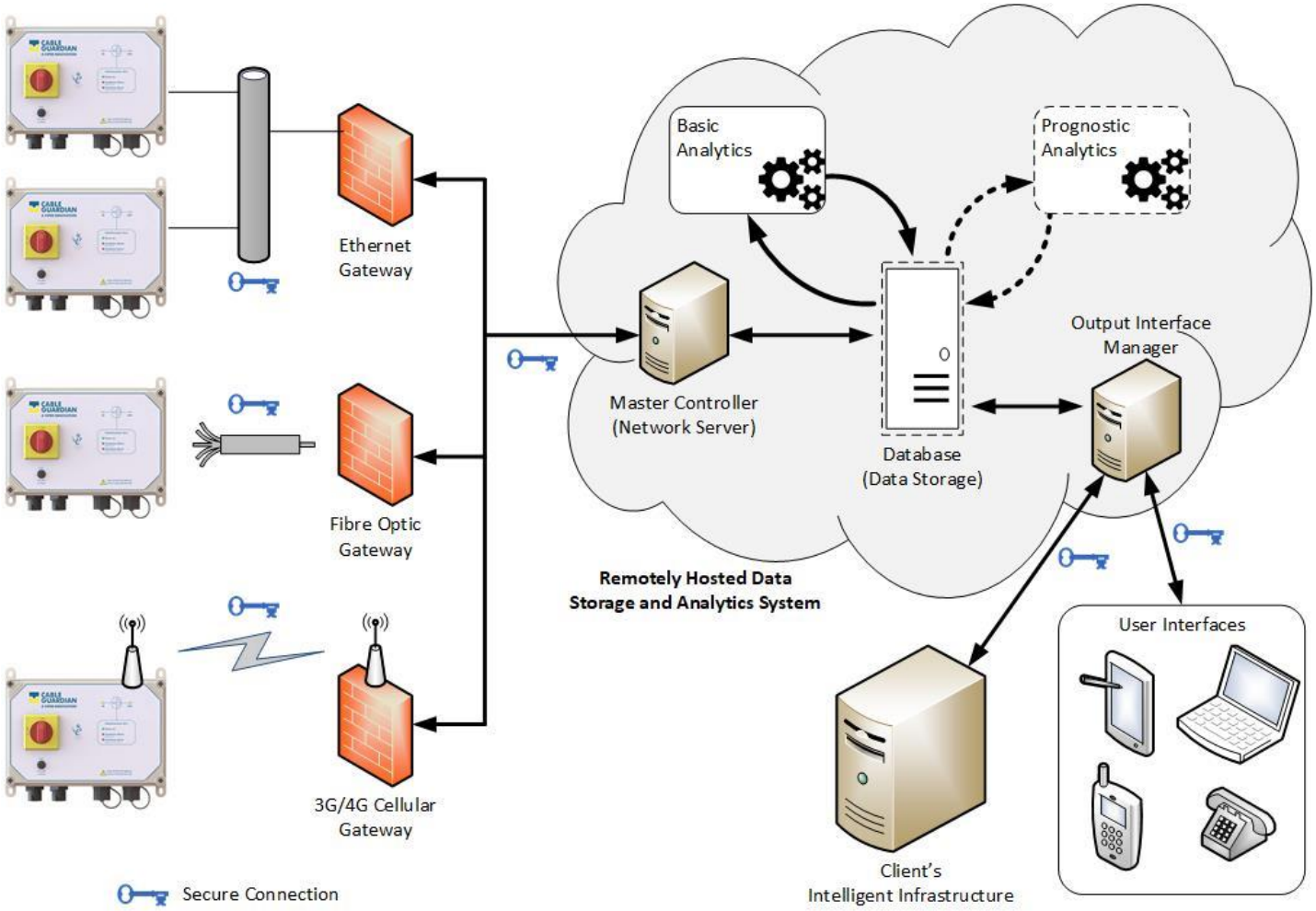
# Challenges Faced by the Rail industry

***Associated with signal failures;***

- *Cable theft, vandalism and general degradation*
- *Safety of rail staff*
- *Public safety*
- *Maintenance costs*
- *Periodic cable testing*
- *Fault location*
- *Fault prevention*
- *Compensation & Fines*

https://cableguardian.viperinnovations.com/

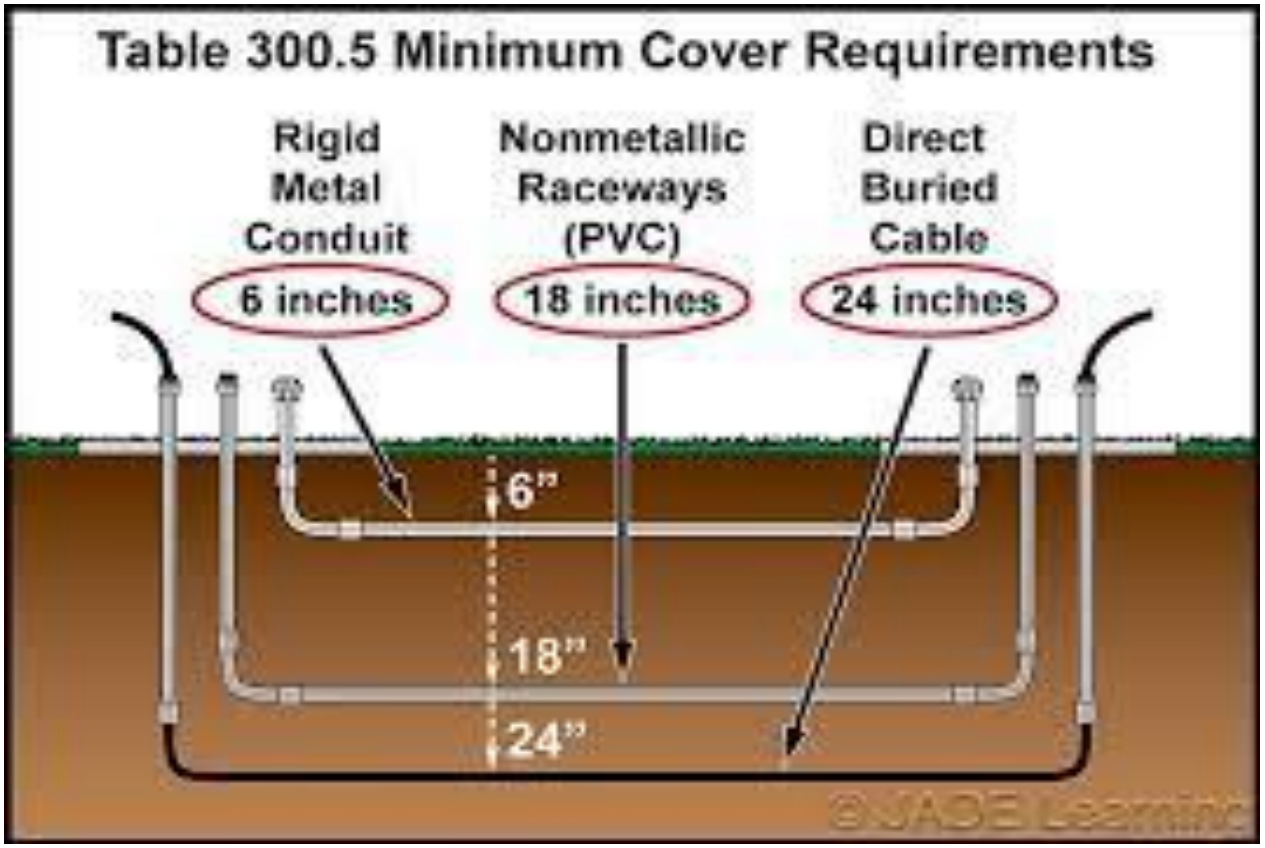
# Full Configuration




https://cableguardian.viperinnovations.com/

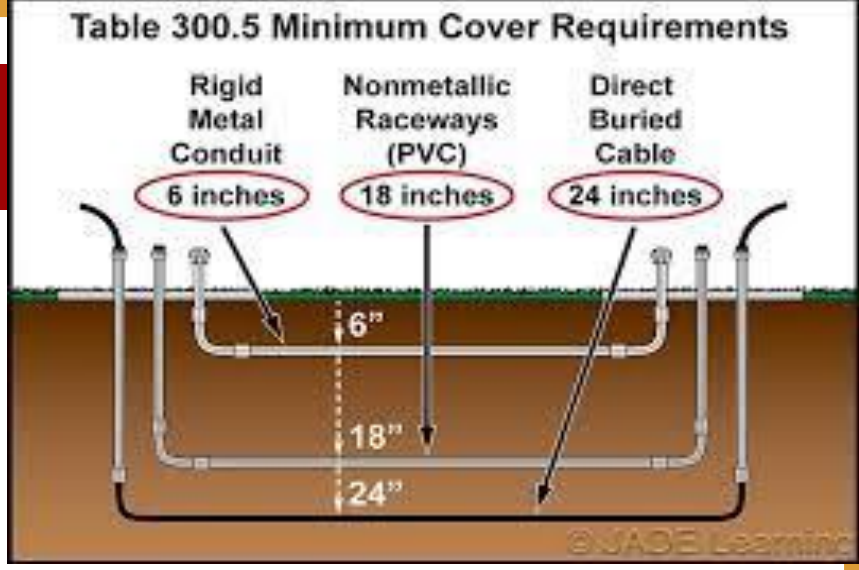
# Buried Cable Faults

## Detection, Protection, Location




Installation Damage, Poor Connections, Shifting/Underground Damage, Water Ingress, Cable Degradation,…

# Detection




**Great Opportunities for Sensor Fusion**

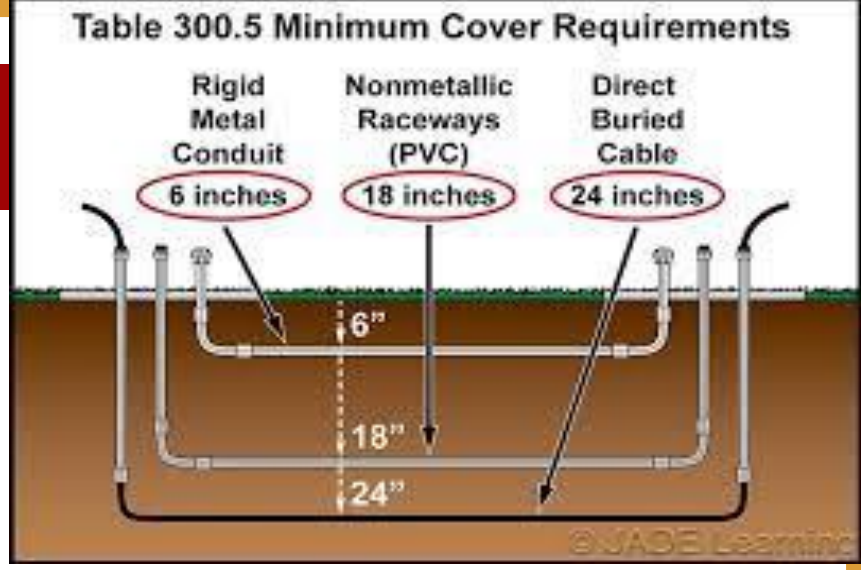
- ***Voltage, Current, Power Testing***
  - *Good for **Detection**, Limited for Location*
- *Visual Inspection*
  - *Not very useful for underground cables*
- ***Resistance/Impedance Testing***
  - *Good for **Detection**, Limited for Location*
- ***Reflectometry***
  - *Can be used for **Detection** & location*

# Protection

Circuit Breakers, Fuses, Arc Fault Circuit Breakers, Reclosers, Rapid Shutdown, Overcurrent Protection,….

**Opportunities to integrate protection and test**

# Location

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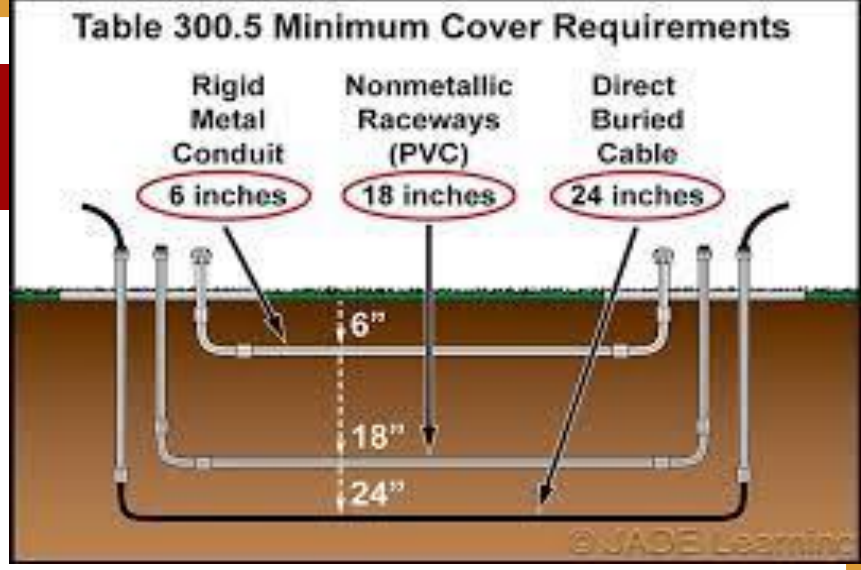
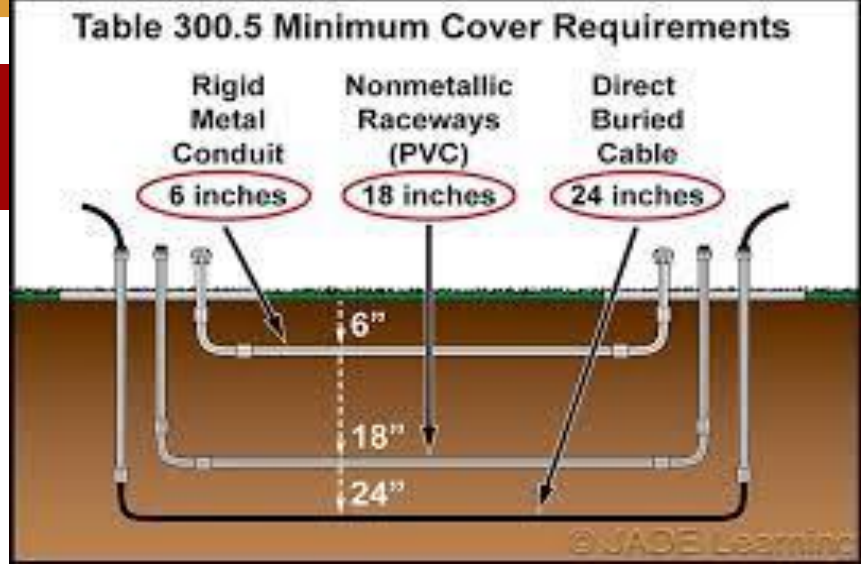
# Prediction




- ***Reflectometry***
  - *Can be used for **Detection & Location***
  - ***Intermittent / Precursor Faults***
    - ***Test continuously while energized***
    - ***Faults are Large, but Intermittent***
  - ***Very Small Degradation***
    - ***Test routinely, high precision >> Likely to be a problem with variability in underground cables***

**Great Opportunities for Sensor Fusion >>**
**IV testing + reflectometry**

# Challenges

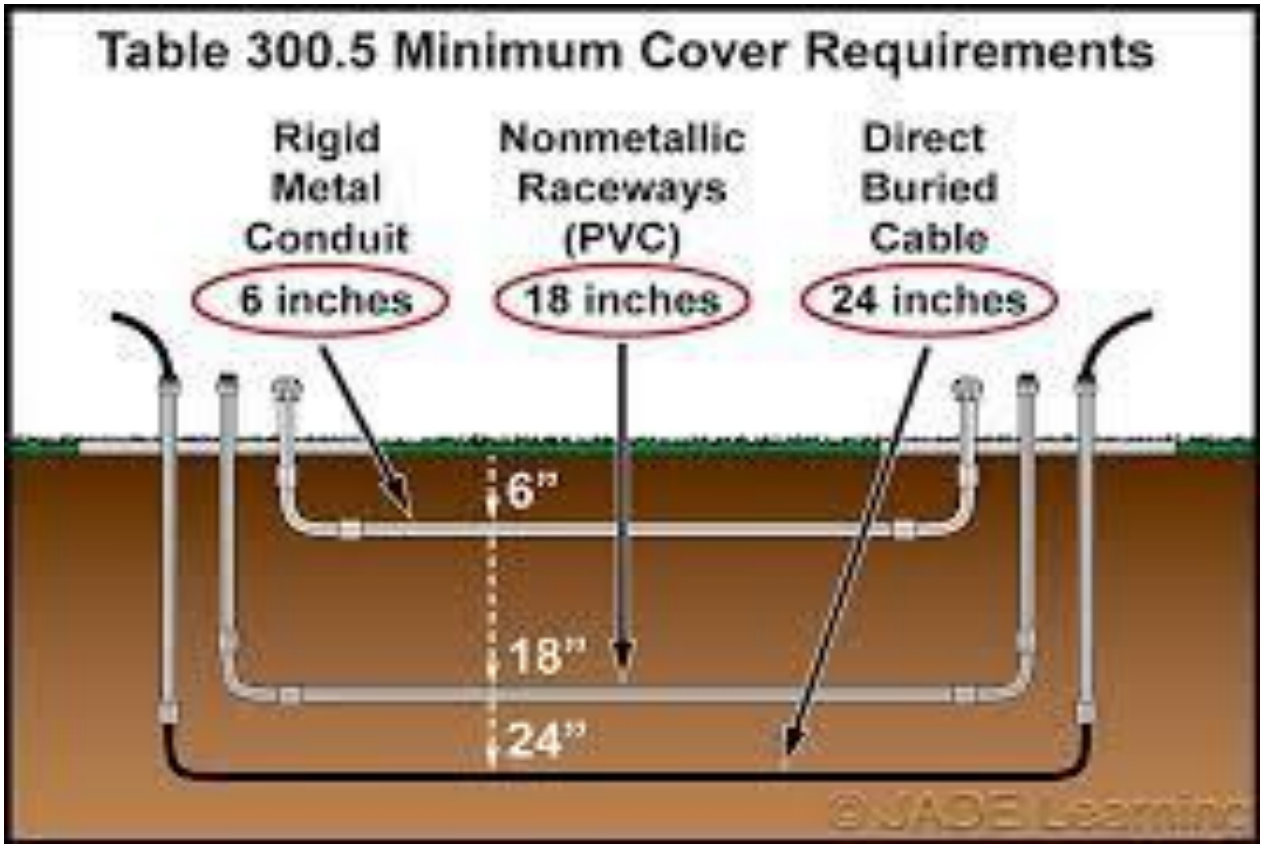



- *Underground is not a precise environment! Lots of variability….*
  - *Integrate over time*
  - *Intermittent faults (wet and dry arcs)*
  - *Sensor Fusion*
  - *"Sacrificial" coverings*
    - *Electrical or Optical testing*

From: TeraFlex

# Buried Cable Faults

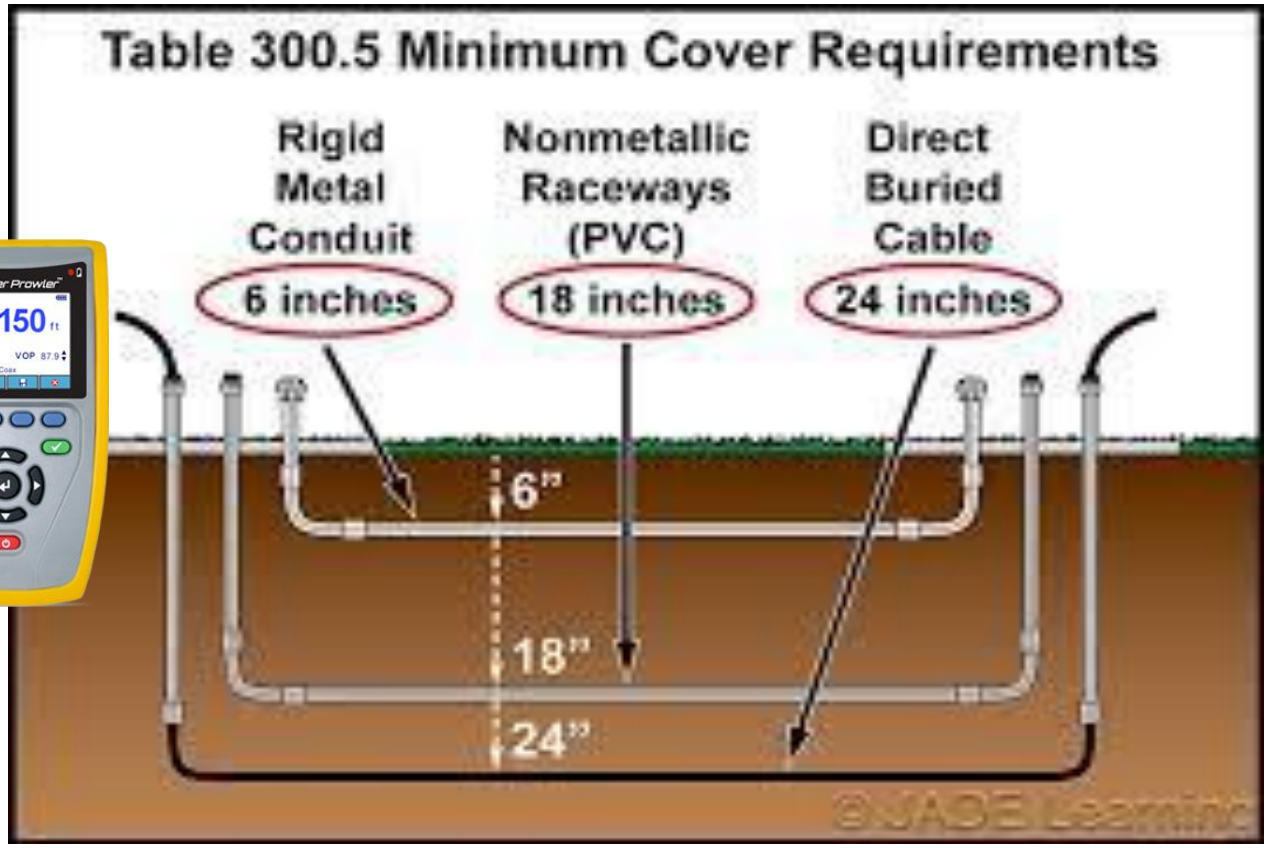
**Detection, Protection, Location >> Prediction**




Installation Damage, Poor Connections, Shifting/Underground Damage, Water Ingress, Cable Degradation,…

# Buried Cable Faults

## Design for Cradle-to-Grave Test System




Cradle: Test During Installation

Mid-Life: Test Continually / Regularly, Data Collection

Later-Life: Degradation testing, Maintenance Optimization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THANK YOU to my TEAM

# EMLab.eng.utah.edu

## Questions?

## cfurse@ece.utah.edu